National Aeronautics and Space Administration

X-Ray Surveyor

Mission Analysis (Version 8)

Oct. 5, 2016

MSFC Advanced Concepts

www.nasa.gov

Change Log

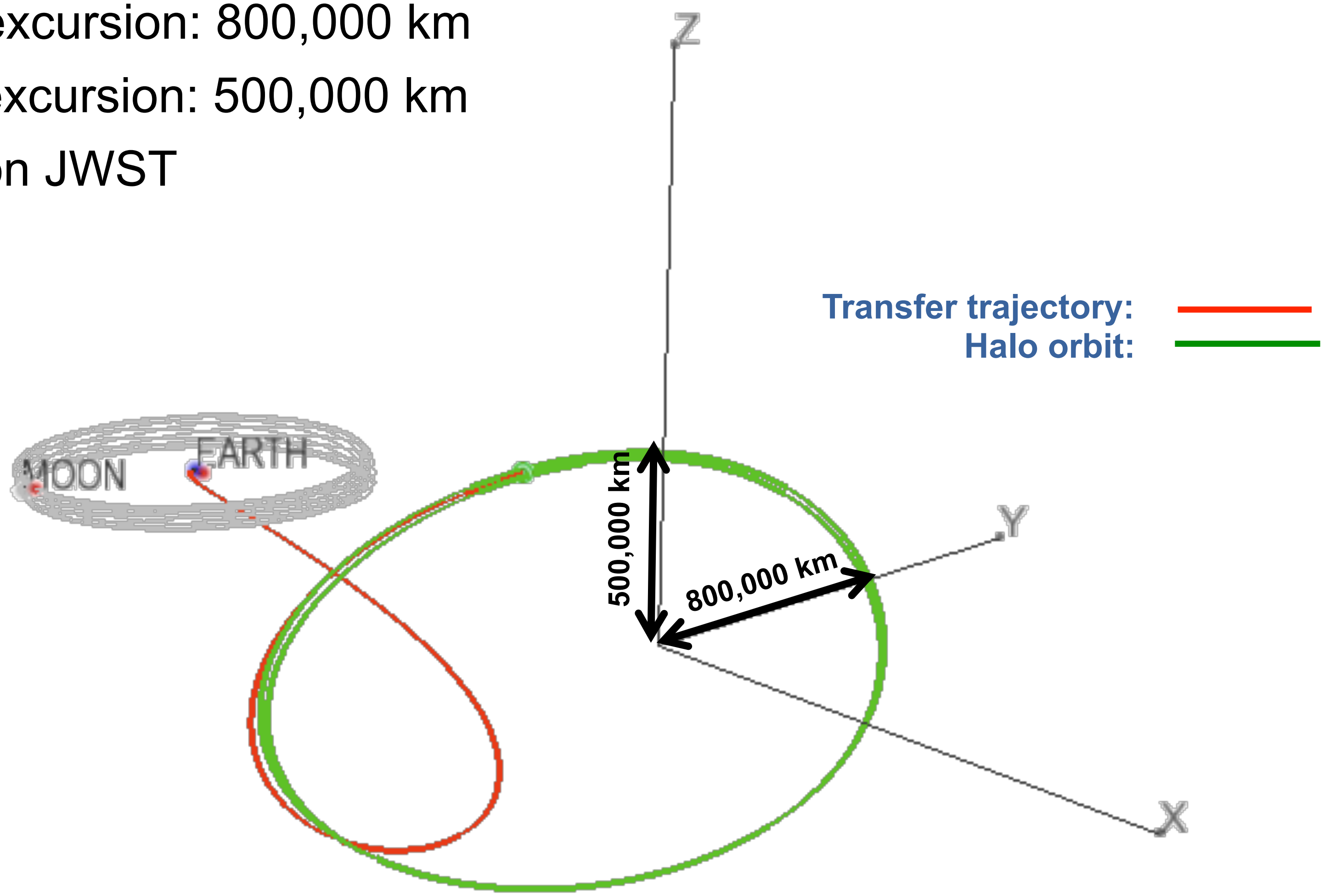
- Version 8
  - Added LEO to the trade space
- Version 7
  - Fixed Version 6 where CTO and DAO delta-v tables were swapped
  - Revised CTO delta-v budget
  - Added explanation about CTO disposal requirement
  - FOMs now include environments
- Version 6
  - Updated Delta-V’s to reflect 30 year consumables requirement
- Version 5
  - Updated timelines; shadow estimates; added FOMs

Orbit Trades

- Several candidate orbits are included in the trade space
  - SE-L2
  - LDRO
  - Chandra-type
  - Drift-away (Earth-trailing)
  - LEO
- Diagram, delta-v budget, and launch vehicle performance to each transfer orbit are provided in the charts below
  - Timelines for each option are currently being generated
- Orbit considerations include:
  - Delta-V requirements
  - Thermal and dynamic stability
  - Distance over time and the effect on communications
  - *Assuming all options can fulfill the sky observing requirements*
    - so no sky coverage analysis is included in these results

Baseline Orbit: SE-L2

- Sun-Earth L2 Halo
  - Direct orbit (no lunar gravity assist), 0 insertion
  - Max Y-excursion: 800,000 km
  - Max Z-excursion: 500,000 km
  - Based on JWST



Delta-V Budget: SE-L2

Event/Maneuver	Start Date	MET (Days)	C3 (km2/s2)	Delta-V (m/s)	ACS Tax (%)	Margin (%)	Total (m/s)
Launch	1/1/30	0.0	-0.70				
Despin	1/1/30	0.0		5	0%	10%	5.5
Post-TTI correction	1/2/30	1.0		41	5%	10%	47.4
Additional correction for late launch	1/2/30	1.0		8	5%	10%	9.2
MCC-1	1/6/30	5.0		7.5	5%	10%	8.7
MCC-2	2/5/30	35.0		5	5%	10%	5.8
MCC-3 / Other (optional)	4/5/30	94.0		5	5%	10%	5.8
Stationkeeping (30 years)	7/4/30	184.0		72.9	5%	10%	84.2
Momentum unloading (30 years)	7/4/30	184.0		43.5	0%	10%	47.9
Disposal	1/1/50	7305.0		1	0%	10%	1.1
TOTALS				**188.9**			**215.5**

Values are based on JWST analyses. MET values are approximate.

Eclipse and Distance: SE-L2

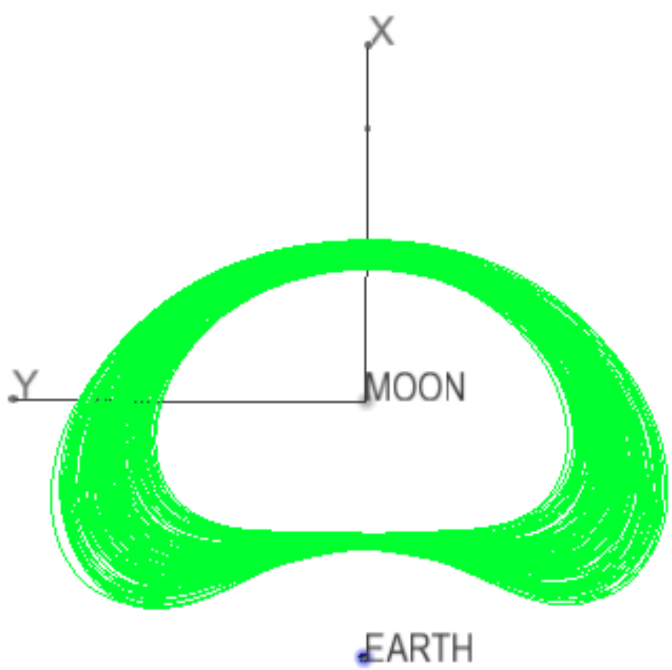
Topic	Value	Units
Time to spacecraft separation	129	minutes
S/C separation in sunlight?	yes*	
Average eclipse	none	minutes
Longest eclipse	none	minutes
Average time between eclipses	na	minutes
Minimum time between eclipses	na	minutes
Max distance** in 1 yr	1,500,000	km
5 yr	1,500,000	km
10 yr	1,500,000	km
20 yr	1,500,000	km

*** Trajectory can be designed such that separation occurs in sunlight, though this may impact launch windows.**

**** These values assume orbit maintenance maneuvers are completed (if required).**

LDRO

- Very stable
  - No disposal required
  - Max distance from Earth
    - 500,000 km



DRO
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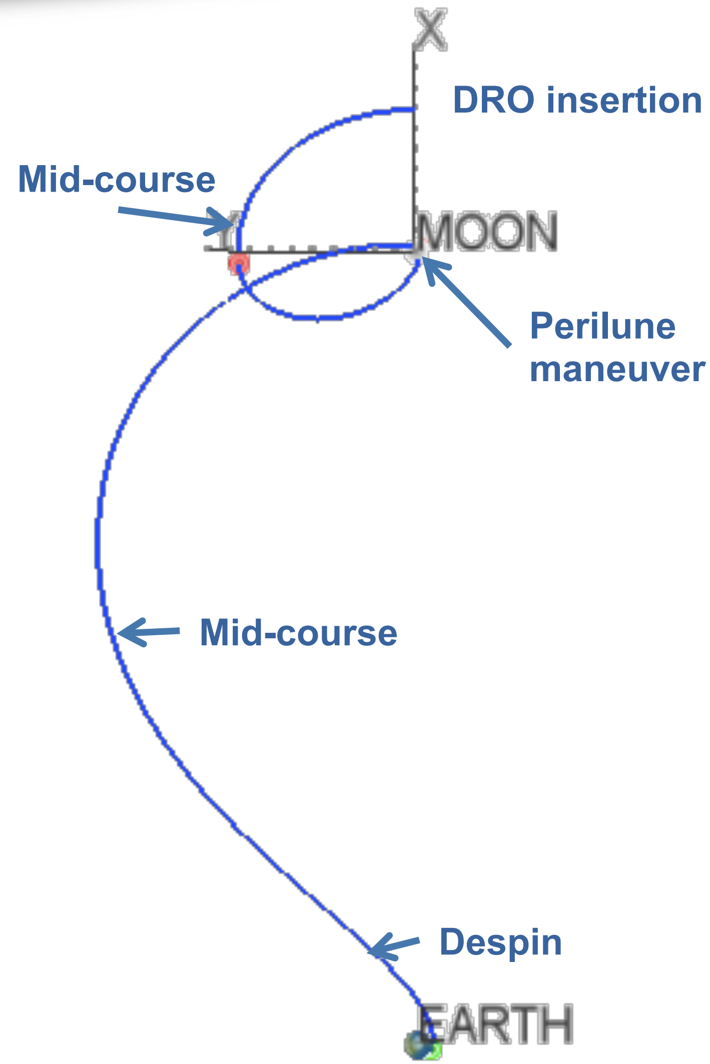

Transfer to DRO
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Delta-V Budget: LDRO

Event/Maneuver	Start Date	MET (Days)	C3 (km2/s2)	Delta-V (m/s)	ACS Tax (%)	Margin (%)	Total (m/s)
Launch	1/1/30	0.0	-1.80				
Despin	1/1/30	0.0		5	0%	10%	5.5
Post-TTI correction	1/2/30	1.0		41	5%	10%	47.4
MCC-1	1/3/30	2.0		50	5%	10%	57.8
Lunar Flyby	1/6/30	5.0		162	5%	10%	187.1
MCC-2	1/10/30	9.0		155	5%	10%	179.0
LDRO Insertion	1/17/30	16.0		3	5%	10%	3.5
Stationkeeping (30 years)	7/4/30	184.0		7.5	5%	10%	8.7
Momentum unloading (30 years)	7/4/30	184.0		43.5	0%	10%	47.9
Disposal	1/1/50	7305.0		10	0%	10%	11.0
TOTALS				**477.0**			**547.7**

Values are based on analysis.

Eclipse and Distance: LDRO

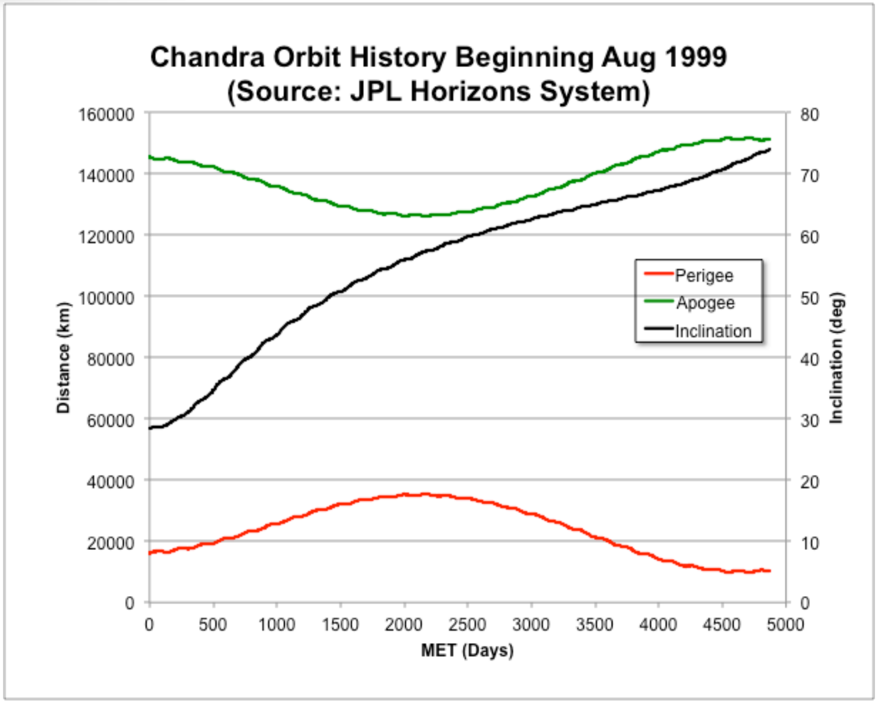
Topic	Value	Units
Time to spacecraft separation	129	minutes
S/C separation in sunlight?	yes*	
Average eclipse	211	minutes
Longest eclipse	706	minutes
Average time between eclipses	118516	minutes
Minimum time between eclipses	12640	minutes
Max distance** in 1 yr	500,000	km
5 yr	500,000	km
10 yr	500,000	km
20 yr	500,000	km

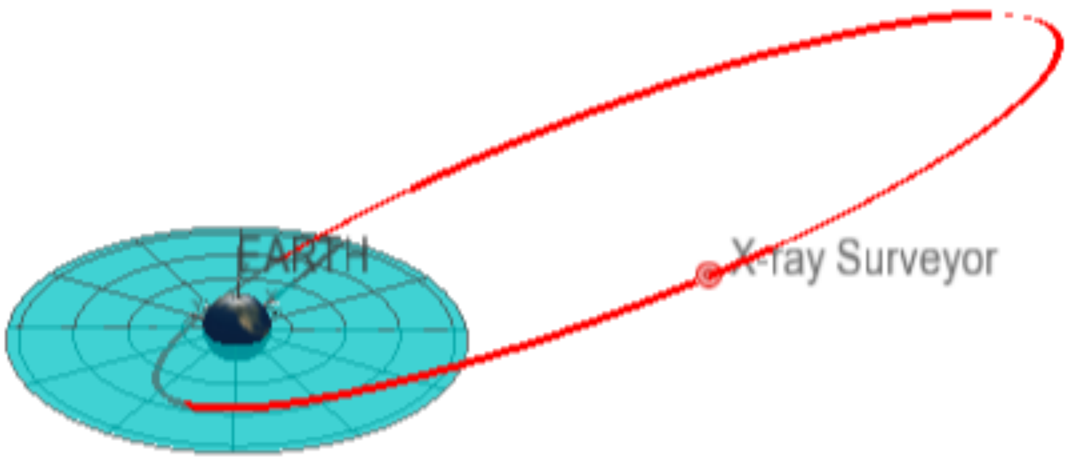
*** Trajectory can be designed such that separation occurs in sunlight, though this may impact launch windows.**

**** These values assume orbit maintenance maneuvers are completed (if required).**

Chandra-Type Orbit (CTO)

- Earth-centered, highly eccentric orbit
  - Placed into final orbit by launch vehicle
  - 16,000 x 133,000 km altitude orbit, 28.5 deg (initially)
  - End-of-life disposal may pose a problem
  - Based on Chandra mission





Delta-V Budget: CTO

Event/Maneuver	Start Date	MET (Days)	C3 (km2/s2)	Delta-V (m/s)	ACS Tax (%)	Margin (%)	Total (m/s)
Launch	1/1/30	0.0	na				
Despin	1/1/30	0.0		5	0%	10%	5.5
Post-TTI correction	1/2/30	1.0		0	5%	10%	0.0
Additional correction for late launch	1/2/30	1.0		0	5%	10%	0.0
MCC-1	1/6/30	5.0		0	5%	10%	0.0
MCC-2	2/5/30	35.0		0	5%	10%	0.0
MCC-3 / Other (optional)	4/5/30	94.0		0	5%	10%	0.0
Stationkeeping (30 years)	7/4/30	184.0		0	5%	10%	0.0
Momentum unloading (30 years)	7/4/30	184.0		43.5	0%	10%	47.9
Disposal	1/1/50	7305.0		302	0%	10%	332.2
TOTALS				**350.5**			**385.6**

Eclipse and Distance: CTO

Topic	Value	Units
Time to spacecraft separation	407	minutes
S/C separation in sunlight?	yes*	
Average eclipse	54	minutes
Longest eclipse	265	minutes
Average time between eclipses	6743	minutes
Minimum time between eclipses	326	minutes
Max distance** in 1 yr	200,000	km
5 yr	200,000	km
10 yr	200,000	km
20 yr	200,000	km

* **Trajectory can be designed such that separation occurs in sunlight, though this may impact launch windows.**

** **These values assume orbit maintenance maneuvers are completed (if required).**

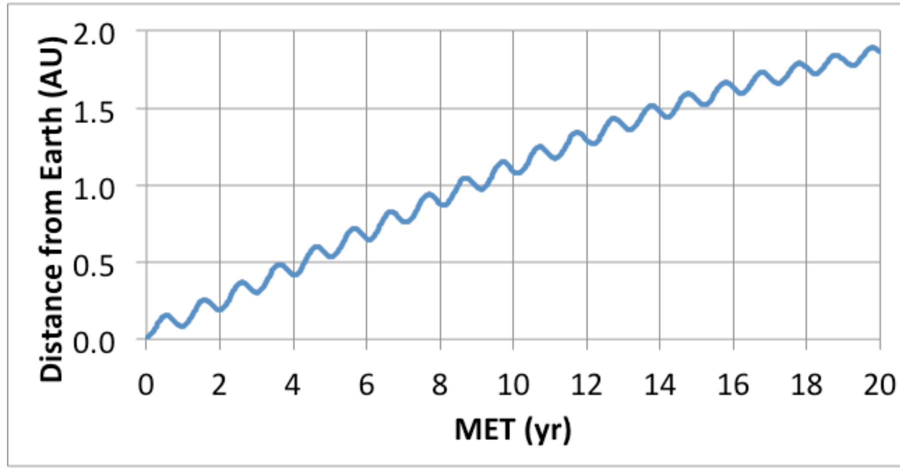
CTO Disposal

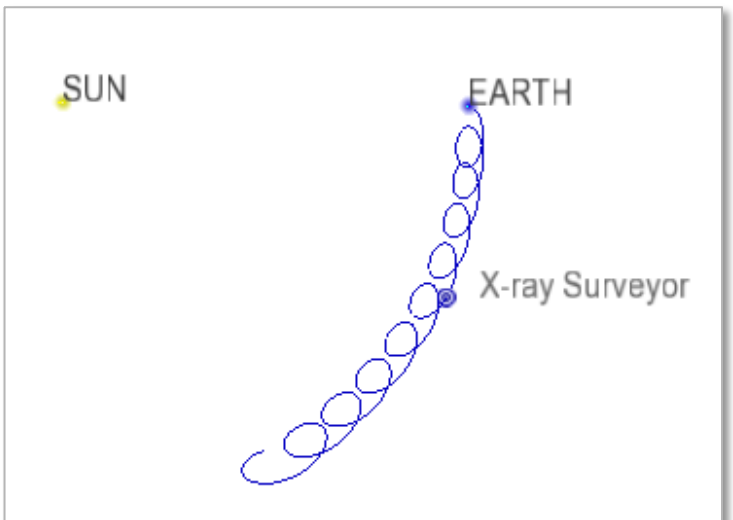
- According to the Orbital Debris Program Office:
  - “The current requirement for the mission you described is to maneuver the spacecraft at the end of mission to a disposal orbit above GEO with a predicted minimum perigee of GEO +200 km (35,986 km) for a period of at least 100 years after disposal.”
- 100 years is a LONG time to propagate an orbit, so used Copernicus with Earth J2, moon, and sun as gravitating bodies
  - To be conservative, targeted GEO + 1200 km as minimum altitude
  - This resulted in a target initial perigee for the disposal orbit of about 39622 km altitude (46000 km radius)
- The delta-v for this maneuver is 302 m/s
  - much less than the initial estimate from DAS

We should assume that disposal is required.

Drift-Away Orbit (DAO), Earth-Trailing

- Launch spacecraft directly into heliocentric orbit
  - No insertion, station-keeping, or disposal maneuvers
  - Distance from Earth to satellite increases over time
  - Based on Kepler mission





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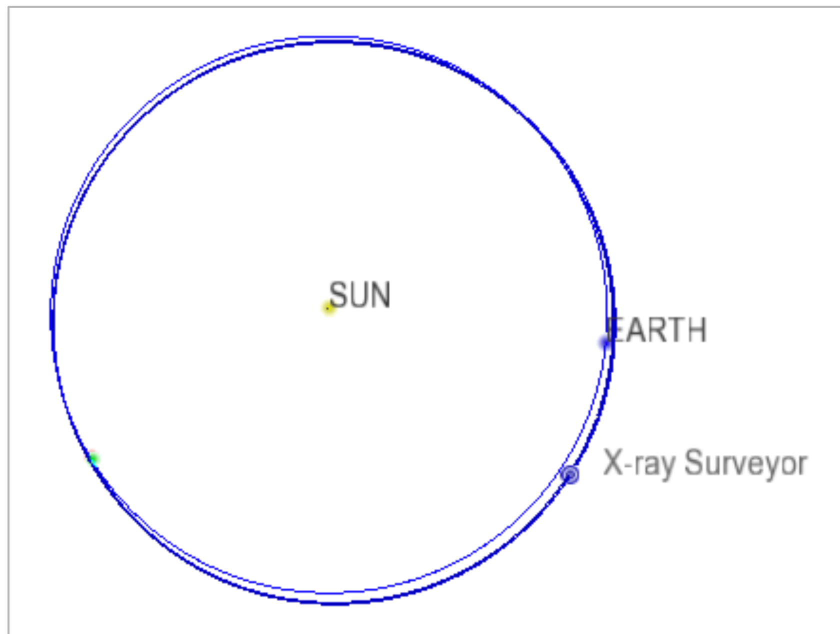


Shown in inertial frame

Delta-V Budget: DAO

Event/Maneuver	Start Date	MET (Days)	C3 (km2/s2)	Delta-V (m/s)	ACS Tax (%)	Margin (%)	Total (m/s)
Launch	1/1/30	0.0	0.61				
Despin	1/1/30	0.0		5	0%	10%	5.5
Post-TTI correction	1/2/30	1.0		0	5%	10%	0.0
Additional correction for late launch	1/2/30	1.0		0	5%	10%	0.0
MCC-1	1/6/30	5.0		0	5%	10%	0.0
MCC-2	2/5/30	35.0		0	5%	10%	0.0
MCC-3 / Other (optional)	4/5/30	94.0		0	5%	10%	0.0
Stationkeeping (30 years)	7/4/30	184.0		0	5%	10%	0.0
Momentum unloading (30 years)	7/4/30	184.0		43.5	0%	10%	47.9
Disposal	1/1/50	7305.0		0	0%	10%	0.0
TOTALS				**48.5**			**53.4**

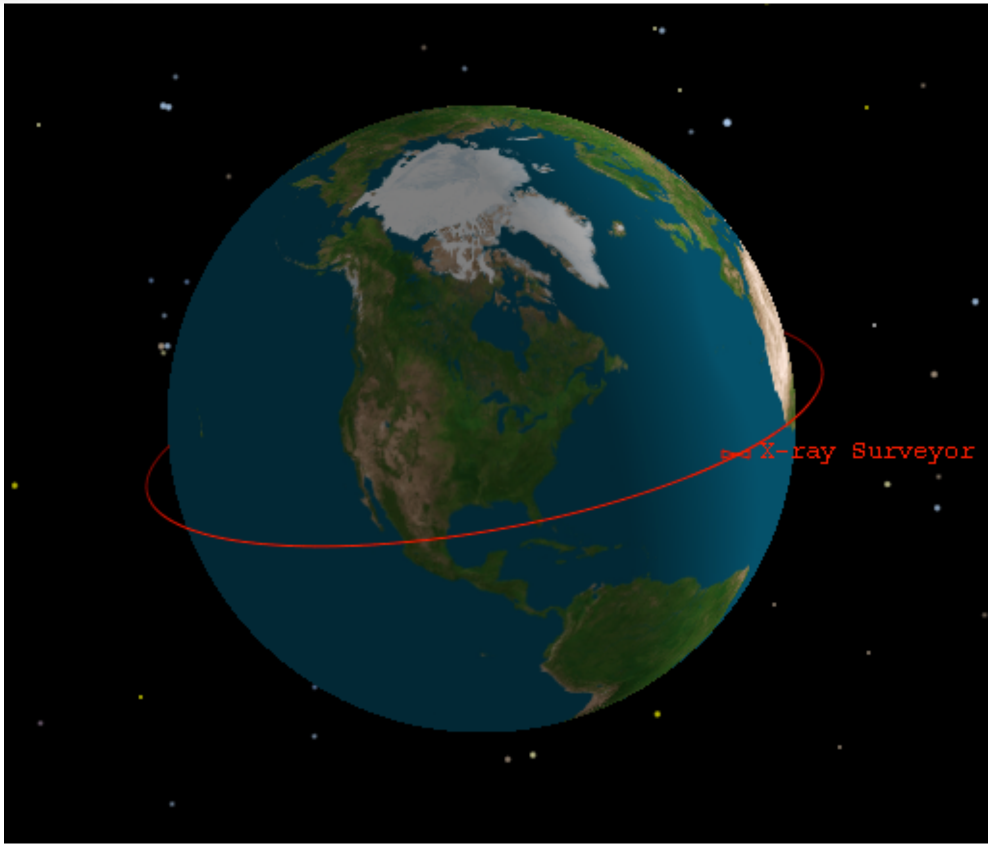
Eclipse and Distance: DAO

Topic	Value	Units
Time to spacecraft separation	129	minutes
S/C separation in sunlight?	yes*	
Average eclipse	none	minutes
Longest eclipse	none	minutes
Average time between eclipses	na	minutes
Minimum time between eclipses	na	minutes
Max distance** in 1 yr	0.1	AU
5 yr	0.6	AU
10 yr	1.1	AU
20 yr	1.8	AU

*** Trajectory will most likely be such that separation occurs in sunlight.**
**** A higher launch C3 can perhaps reduce these values. Analysis is pending.**

Low Earth Orbit (LEO)

- Launch from CCAFS
  - 550 km circular orbit, 28.5 degree inclination
  - Because of Earth perturbations, momentum unloading is higher for this orbit
  - Because of atmospheric drag, orbit maintenance is frequently required
    - Used DAS to estimate the aerodynamic area as well as the orbit decay rate
    - Assumed a mass-to-area ratio of 0.014 kg/m^2



Delta-V Budget: LEO

Event/Maneuver	Start Date	MET (Days)	C3 (km2/s2)	Delta-V (m/s)	ACS Tax (%)	Margin (%)	Total (m/s)
Launch	1/1/30	0.0	na				
Despin	1/1/30	0.0		5	0%	10%	5.5
Launch vehicle error correction	1/2/30	1.0		10	5%	10%	11.6
Additional correction for late launch	1/2/30	1.0		0	5%	10%	0.0
MCC-1	1/6/30	5.0		0	5%	10%	0.0
MCC-2	2/5/30	35.0		0	5%	10%	0.0
MCC-3 / Other (optional)	4/5/30	94.0		0	5%	10%	0.0
Stationkeeping (30 years)	7/4/30	184.0		240	5%	10%	277.2
Momentum unloading (30 years)	7/4/30	184.0		60	0%	10%	66.0
Disposal	1/1/50	7305.0		161	5%	10%	186.0
TOTALS				**476.0**			**546.2**

Assumed 550 km altitude circular orbit, 28.5 degrees.
Except for the disposal maneuver, these are rough estimates.

Eclipse and Distance: LEO

Topic	Value	Units
Time to spacecraft separation	??	minutes
S/C separation in sunlight?	??	
Average eclipse	35	minutes
Longest eclipse	??	minutes
Average time between eclipses	60	minutes
Minimum time between eclipses	??	minutes
Max distance** in 1 yr	600	km
5 yr	600	km
10 yr	600	km
20 yr	600	km

** Assumes station keeping and a starting orbit of 550 km circular altitude.

Eclipse analysis not done, but can be completed if the team decides to examine this option further.

Figures of Merit (FOMs)

- Subjective ranking of the different options
  - Use the "graduate student" grading scale
    - A = good work
    - B = need to improve
    - C = get the heck out of here

Grade scale	Points
A	1.00
B	0.75
C	0.50

	Total Score	Launch Vehicle	Delta-V	Duration	Thermal	Comm	Environ-ment
Max Points -->	**100**	10	15	20	20	20	15
SE-L2	**91**	A	A	A	A	B	B
Drift-away	**76**	A	A	C	A	C	B
LDRO	**84**	A	C	A	B	A	B
CTO	**76**	B	B	A	C	A	C
LEO	**68**	A	C	B	C	C	A

WINNER: SE-L2

FOM Rationale

	Launch Vehicle	Delta-V	Duration	Thermal	Comm	Environ-ment
	How large of a launch vehicle is required?	Smaller budget is better. Note that disposal is a major issue for the CTO.	Will the observatory remain close enough to allow reasonable comm?	How stable is the thermal environment?	How large must the comm system be to provide the science data downlink?	How bad is the radiation and meteroid environment in this orbit?
SE-L2	SE-L2, Drift-away, and LDRO are roughly similar in LV requirements	Budget is not bad, but the orbit maintenance adds up over 20+ years.	Stays within 0.1 AU from Earth.	Very stable.	30 times further than LDRO, making high data rates challenging.	Ionizing radiation: no geomagnetic shielding from solar particle events which drive total dose. Galactic cosmic rays drive single event effects. Meteoroids are same as interplanetary space.
Drift-away	SE-L2, Drift-away, and LDRO are roughly similar in LV requirements	No orbit maintenance or correction maneuvers results in the lowest DV budget.	Reaches 0.3+ AU after a few years.	Very stable.	System would lose performance with distance.	Ionizing radiation: no geomagnetic shielding from solar particle events which drive total dose. Galactic cosmic rays drive single event effects. Meteoroids are same as interplanetary space.
LDRO	SE-L2, Drift-away, and LDRO are roughly similar in LV requirements	Low orbit maintenance, but transfer trajectory does require some maneuvers.	Always less than 500,000 km from Earth.	Fairly stable, though there could be some shadowing during the mission.	LDRO and CTO would be simular systems being same order of distance.	Ionizing radiation: no geomagnetic shielding from solar particle events which drive total dose. Galactic cosmic rays drive single event effects. Meteoroids are same as interplanetary space.
CTO	CTO requires more performance (i.e., 1 or 2 more SRBs).	While Chandra has required little orbit maintenance, the new orbital debris standards may require a disposal maneuver at the end of any new missions planned for this orbit.	Always less than 200,000 km from Earth.	Least stable of the options since the satellite passes within 16,000 km of Earth every orbit.	Available DSN link may be intermittent at times, restricting specific link times.	Ionizing radiation environment is same as other candidates PLUS the passage through the radiation belts which contributes significant total dose and single event effects. Meteoroid environment is similar to others but with mild enhancement at perigee due to gravitational focusing (speeds up slower meteoroids), however spacecraft spends little time that low and apogee is same interplanetary environment.
LEO	Greatest launch vehicle performance is to LEO.	Controlled reentry required. Orbit maintenance required to avoid reentry during lifetime, which can get expesive for long missions.	Duration is completely dependent on station-keeping and orbit maintenance.	Lots of thermal cycling, reflected heat from Earth.	In LEO, the NEN will be used for comm. S-band is limited to 5Mbs per customer, and X-band is limited to 10Mbps.	In LEO, the observatory is shielded from solar particle events.

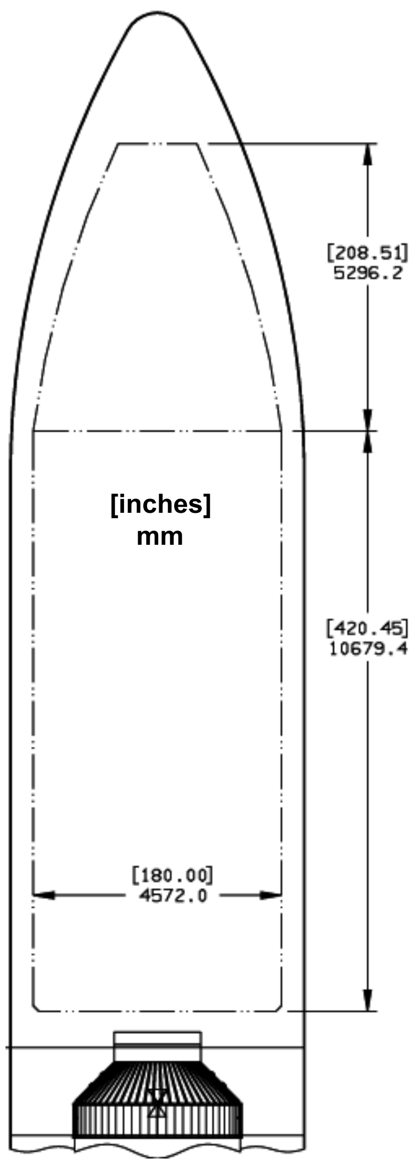
Launch Vehicle Selection and Performance

- Baseline Atlas V 5-meter *long shroud*
  - Preliminary length and diameter estimates for the X-Ray Surveyor observatory indicate this size of shroud will be required
  - Estimates below are for the short shroud, so actual performance will be slightly less
  - Since launch is 2030, actual performance numbers are only useful for getting an idea of the performance available in the future

Source -->	NLS quote		NLS website	NLS website	NLS website
Orbit type -->	Elliptical Chandra-type		Drift-away	SE-L2 transfer	LDRO transfer
Altitude or C3 -->	16000 x 133000 km		C3 = 0.61 km2/s2	C3 = -0.7 km2/s2	C3 = -1.8 km2/s2
Burn profile -->	2-burn	3-burn			
Atlas V 521	3355	3305	4115	4250	4345
Atlas V 531	3995	3950	4885	5005	5110
Atlas V 551	TBD	TBD	6040	6185	6310
Falcon 9 (v1.1)*	TBD	TBD	TBD	3715	TBD
Delta IV Heavy	TBD	TBD	10490	10735	10945

*** Note: performance data for the Full Thrust option of the Falcon 9 was not available, but is not expected to increase performance.**

Atlas V 5xx Series Summary



5m long shroud

PAYLOAD FAIRING (PLF)

Features	5-m Short	5-m Medium	5-m Long
Diameter:	5.4 m	5.4 m	5.4 m
Length:	20.7 m	23.4 m	26.5 m
Mass:	3,540 kg	4,019 kg	4,394 kg

Subsystems

Fairing:	Bisector; Sandwich Construction with Graphite Epoxy Face Sheets & an Aluminum Honeycomb Core
Boattail:	Fixed, Composite Sandwich Const
Separation:	Vertical Separation by a Linear Piston & Cylinder Activated by a Pyrotechnic Cord; Horizontal Separation by an Expanding Tube Shearing a Notched Frame, Activated by a Pyrotechnic Cord

COMMON CENTAUR

Features	All Common with Atlas 400 Series
Size:	3.05-m Dia x 12.68-m Length with Extended Nozzle
Inert Mass:	2,138 kg
Propellant:	20,830-kg LH_2 & LO_2
Guidance:	Inertial
Subsystems	
Structure:	Pressure Stabilized Stainless Steel Tanks Separated by Common Ellipsoidal Bulkhead
Propulsion:	One or Two Pratt & Whitney Restartable Engine(s)
— Model:	RL10A-4-2
— Thrust:	99.2 kN (SEC) 198.4 kN (DEC)
— I_{SP}:	450.5 s
(SEC)	One Electromechanically Actuated 51-cm Columbium Fixed Nozzle Four 27-N Hydrazine Thrusters Eight 40-N Lateral Hydrazine Thrusters
(DEC)	Two Hydraulically Actuated 51-cm Columbium Extendible Nozzles Eight 40-N Lateral Hydrazine Thrusters Four 27-N Hydrazine Thrusters
Pneumatics:	Common with Atlas V 400 Series
Avionics:	Common with Atlas V 400 Series
Insulation:	Polyvinyl Chloride Foam (1.6-cm Thick), Modified Adhesive Bonding with Optional Radiation Shields

SOLID ROCKET BOOSTERS (SRB)

Zero-to-Five	Ground-Lit
Size:	155-cm Dia x 19.5-m Length
Mass:	46,559 kg (Each Fueled)
Thrust:	1,361 kN (Each)
I_{SP}:	275 s
Nozzle Cant:	3 deg

CENTAUR INTERSTAGE ADAPTER (C-ISA LARGE)

Features	
Size:	3.81-m Dia x 4.46-m Length
Mass:	2,292 kg (Includes ISA, Aft Stub Adapter and Boattail)
Subsystems	
Structure:	Composite Sandwich (Aluminum Core/Graphite Epoxy Face Sheets)

CCB CYLINDRICAL INTERSTAGE ADAPTER

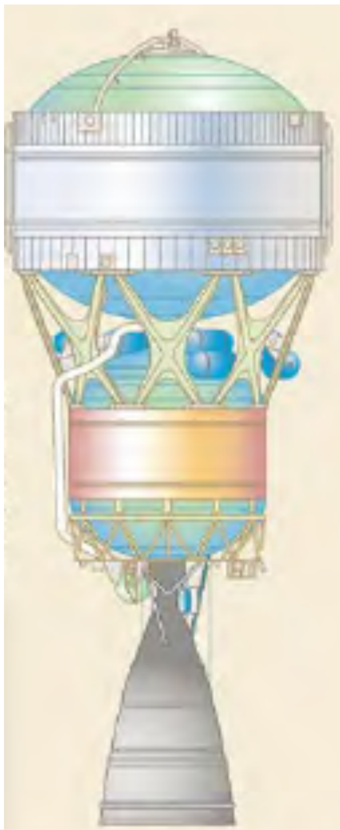
Features	
Size:	3.81-m Dia x 0.32-m Length
Mass:	282 kg
Subsystems	
Structure:	Aluminum Machined Rolled-Ring Forging

COMMON CORE BOOSTER™ (CCB)

Features	Common with Atlas V 400 Series
Size:	3.81-m Dia x 32.46-m Length
Propellant:	284,089-kg LO_2 & RP-1
Inert Mass:	21,336 kg for 55Z Configuration
Guidance:	From Upper Stage
Subsystems	
Structure:	Structurally Stable Aluminum Isogrid Tanks; Integrally Machined Aft Transition Structure; Composite Heat Shield
Separation:	8 Retro Rockets
Propulsion:	Pratt & Whitney/NPO Energomash RD-180 Booster Engine (2 Chambers) SL 100% Thrust = 3,827 kN, I_{SP} = 311.3 s Vac 100% Thrust = 4,152 kN, I_{SP} = 338.4 s
Pneumatics:	Helium for Tank Pressurization, Computer-Controlled Pressurization System
Hydraulics:	Integral with Engine Provides Gimbal Control
Avionics:	Flight Control, Flight Termination, Telemetry, Redundant Rate Gyros, Electrical Power

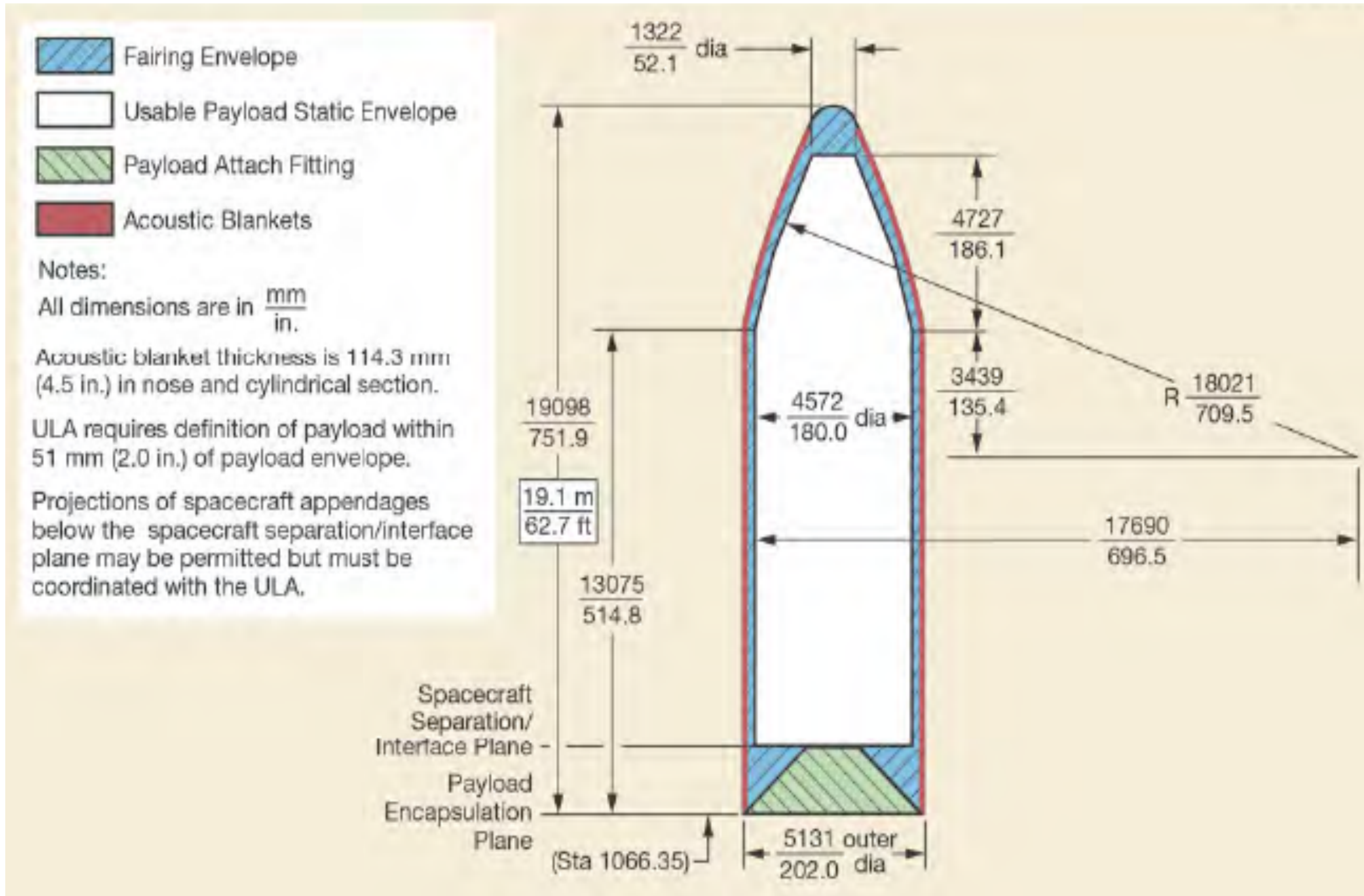
Delta-IV Heavy Summary

Second stage.



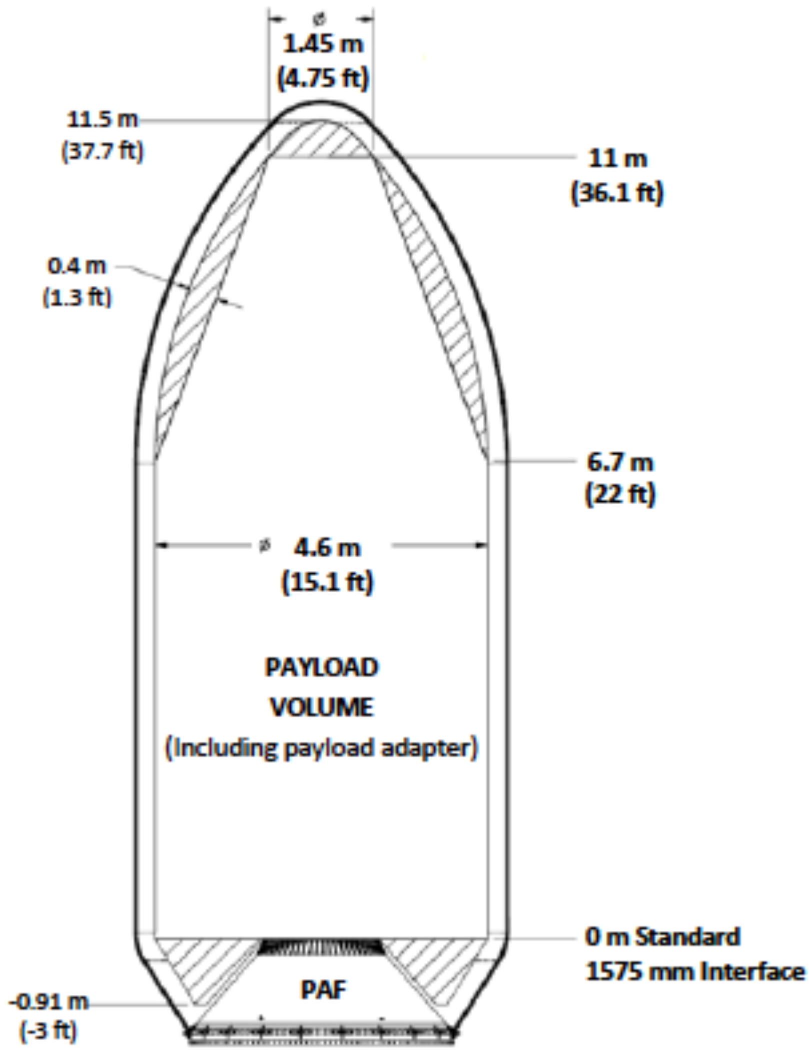
- 3.2-m-dia stretched LO_2 tank
- 5-m-dia LH_2 tank
- Pratt & Whitney RL10B-2 engine

Payload static envelope for the composite fairing.



Falcon 9 Summary

Payload dynamic envelope.



Second stage summary.

Item	Description
Engine	Merlin
Quantity	1
Burn Time, max	387 sec
Max Thrust	934000 N (210,000 lbf)

Estimated Acceleration During Departure

- Estimated maximum acceleration during the Earth departure burn using Atlas V
  - Use Centaur single engine configuration (Atlas V)
    - Inert mass of 2138 kg
    - Observatory masses of 3000 and 4500 kg
    - Max thrust of 99,200 N
  - Results tabulated below
    - Does not include adapter, which would lower the maximum acceleration slightly
    - So long as observatory mass is greater than about 3000 kg, the acceleration during earth departure should be less than 2 g's

Observatory Mass (kg)	Max Acceleration (g's)	Centaur Thrust (N)	Centaur Inert Mass (kg)
3000	1.97	99200	2138
4500	1.52	99200	2138

If mass > 3000 kg, departure acceleration will be less than 2 g's